

PROMPT IRON ENRICHMENT, TWO *R*-PROCESS COMPONENTS, AND ABUNDANCES IN VERY METAL-POOR STARS

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ABSTRACT

We present a model to explain the wide range of abundances for heavy *r*-process elements (mass number $A > 130$) at low [Fe/H]. This model requires rapid star formation and/or an initial population of supermassive stars in the earliest condensed clots of matter to provide a prompt or initial Fe inventory. Subsequent Fe and *r*-process enrichment was provided by two types of supernovae: one producing heavy *r*-elements with no Fe on a rather short timescale and the other producing light *r*-elements ($A \leq 130$) with Fe on a much longer timescale.

Subject headings: Galaxy: evolution — Stars: abundances — Stars: Population II

1. INTRODUCTION

We present a phenomenological model for the abundances of Fe and heavy (mass number $A > 130$) and light ($A \leq 130$) *r*-process elements (*r*-elements) in very metal-poor stars. These stars formed early in Galactic history when only a small number of massive stars had evolved to become Type II supernovae and added heavy elements to the interstellar medium (ISM). Observations (e.g., McWilliam et al. 1995; McWilliam 1998) show that there is a lack of correlation between the “metallicity” measured by [Fe/H] and abundances of *r*-elements above $A \sim 135$ (e.g., Ba and Eu) for stars with $-3.1 \lesssim \text{[Fe/H]} \lesssim -2.5$. This disagrees with the view that Fe and *r*-elements are always coproduced by supernovae. Our approach to account for this result is based on a two-component *r*-process model (Wasserburg, Busso, & Gallino 1996; Qian, Vogel, & Wasserburg 1998; Qian & Wasserburg 1999, hereafter QW99) which attributes heavy *r*-nuclei to high frequency supernovae (H events) and light *r*-nuclei to less frequent ones (L events). We propose that prompt production of Fe with minor coproduction of heavy *r*-elements in the earliest era of the Galaxy first enriched the ISM up to [Fe/H] ~ -3 . Subsequent production of $A > 130$ nuclei with negligible coproduction of Fe by H events then resulted in a wide range of abundances for heavy *r*-elements at $-3.1 \lesssim \text{[Fe/H]} \lesssim -2.5$. We associate further Fe enrichment of the ISM for [Fe/H] > -3 with L events. Addition of H and L events over a sufficiently long timescale then led to a correlation between [Fe/H] and abundances of heavy *r*-elements at [Fe/H] $\gtrsim -2.5$.

Mathews, Bazan, & Cowan (1992) discussed using Galactic chemical evolution to constrain the site of the *r*-process. A number of recent studies (Ishimaru & Wanajo 1999; Tsujimoto, Shigeyama, & Yoshii 1999; McWilliam & Searle 1999; see also Raiteri et al. 1999) focused on the relationships between [Fe/H] and abundances of heavy *r*-elements in the early Galaxy. A common consensus is that chemical enrichment of the ISM at very early times was grossly inhomogeneous and diverse yields of individual supernova events had dramatic effects on abundances in very metal-poor stars. Our present work differs from previous

studies in that the diversity in *r*-process production by supernovae is introduced through the two-component *r*-process model based on solar system data independent of the stellar observations. Further, we propose a prompt mechanism for Fe production considering special conditions of the early Galaxy. In §2 we describe the framework of two *r*-process components. In §3 we use this together with a postulated prompt Fe source to explain the observational results on abundances (especially for Ba and Eu) in the early Galaxy. We discuss prompt Fe production and give conclusions in §4.

2. TWO *R*-PROCESS COMPONENTS

Observations by Sneden et al. (1996, 1998) demonstrated that abundances of *r*-elements in the Pt peak ($A \sim 195$) and down to Ba ($A \sim 135$) in CS 22892–052 ([Fe/H] = -3.1), HD 115444 ([Fe/H] = -2.77), and HD 126238 ([Fe/H] = -1.67) are in remarkable accord with the solar system *r*-process abundance pattern (the solar *r*-pattern). Assuming that a single *r*-pattern extends from Ba to the actinides above the Pt peak, Cowan et al. (1997, 1999) discussed using the Th/Eu ratio as a Galactic chronometer. However, the discovery of ^{182}Hf (lifetime $\bar{\tau}_{182} = 1.30 \times 10^7$ yr) in meteorites with $(^{182}\text{Hf}/^{180}\text{Hf})_{\text{SSF}} = 2.4 \times 10^{-4}$ (Harper & Jacobsen 1996; Lee & Halliday 1995, 1997) at the time of solar system formation (SSF) provided a new twist to our understanding of the *r*-process. Although both ^{182}Hf and ^{129}I ($\bar{\tau}_{129} = 2.27 \times 10^7$ yr) are produced essentially only by the *r*-process, the ^{182}Hf data and abundance ratio $(^{129}\text{I}/^{127}\text{I})_{\text{SSF}} = 10^{-4}$ (Reynolds 1960; see also Brazzle et al. 1999) cannot be explained by a single type of *r*-process events. Based on this, Wasserburg et al. (1996) concluded that there had to be at least two distinct types of *r*-process events: one (H) occurring on a timescale $\Delta_H \sim 10^7$ yr, commensurate with that for replenishment of a typical molecular cloud with fresh supernova debris, and the other (L) occurring on a much longer timescale $\Delta_L \sim 10^8$ yr. They further pointed out that relative to the solar *r*-pattern, there should be frequent abundance excesses of *r*-elements in the Pt peak over those in the

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$A \sim 130$ peak below Ba at low metallicities. Qian et al. (1998) showed that in a two-component model to account for the solar r -pattern, the total mass yield of an L event must be ~ 10 times that of an H event. They also showed that it is not readily possible to produce the $A \sim 130$ peak without substantially populating the region beyond this peak. They further speculated that H events might be associated with production of black holes and L events with production of neutron stars.

A preliminary report on the observed Ag ($A \sim 107$) abundance in CS 22892-052 by Cowan & Sneden (1999) appeared to support the meteoritic prediction that more than one type of r -process events may be required. Based on this, Qian & Wasserburg (QW99) sought to establish a quantitative basis for predicting the yields of r -elements in H and L events. Their model uses the following assumptions: (1) each H or L event has fixed r -process yields; (2) the products of individual H and L events are mixed with a “standard” mass of hydrogen in the ISM; and (3) the solar system inventory of all r -nuclei (both stable and radioactive) are the result of production by H and L events over a time $T_{\text{UP}} \approx 10^{10}$ yr preceding SSF. The timescales for occurrence of H and L events in a volume corresponding to the standard mixing mass of hydrogen are Δ_H and Δ_L . Under the above assumptions, at the time of SSF, the number of nuclei for a stable nuclide \mathcal{S} (e.g., ^{127}I or ^{182}W) mixed with a standard mass of hydrogen is

$$N_{\mathcal{S}}(t_{\text{SSF}}) = Y_{\mathcal{S}}^H \frac{T_{\text{UP}}}{\Delta_H} + Y_{\mathcal{S}}^L \frac{T_{\text{UP}}}{\Delta_L}, \quad (1)$$

while that for a radioactive nuclide \mathcal{R} with $\bar{\tau}_{\mathcal{R}} \ll T_{\text{UP}}$ (e.g., ^{129}I or ^{182}Hf) is

$$N_{\mathcal{R}}(t_{\text{SSF}}) \approx \frac{Y_{\mathcal{R}}^H \exp(-\vartheta \Delta_H / \bar{\tau}_{\mathcal{R}})}{1 - \exp(-\Delta_H / \bar{\tau}_{\mathcal{R}})} + \frac{Y_{\mathcal{R}}^L}{\exp(\Delta_L / \bar{\tau}_{\mathcal{R}}) - 1}. \quad (2)$$

In equations (1) and (2) Y^H or Y^L denotes the yield in an H or L event. The yield for a radioactive species is taken to be about the same as that for the corresponding stable nuclide. In equation (2) the interval between SSF and the last L event is assumed to be Δ_L , while that between SSF and the last H event is specified by ϑ ($0 \leq \vartheta \leq 1$). From the meteoritic data on ^{129}I and ^{182}Hf , it was found that $\Delta_H \leq 1.85 \times 10^7$ yr and $\Delta_L \geq 1.06 \times 10^8$ yr for $\vartheta = 1$ (scenario A). Further, the yields for ^{127}I and ^{182}W in an L event relative to those in an H event, Y_{127}^L / Y_{127}^H and Y_{182}^L / Y_{182}^H , are rather strongly constrained for all cases bracketed by scenarios A and B ($\vartheta = 0$). Given ϑ , Δ_H , and Δ_L , the yields for ^{127}I and ^{182}W in an H or L event can be obtained from the relevant solar system data through equations (1) and (2).

To generalize the results to other r -nuclei, Qian & Wasserburg (QW99) assumed that the yield template for $A > 130$ nuclei associated with ^{182}W is the same as the corresponding solar r -pattern for both H and L events based on the observations by Sneden et al. (1996, 1998). The yields for $A \leq 130$ nuclei associated with ^{127}I in an H or L event were also chosen to follow the corresponding solar r -pattern. Consequently, the yield for a stable nucleus \mathcal{S} with mass number A in an L event relative to that in an H event is $Y_{\mathcal{S}}^L / Y_{\mathcal{S}}^H = Y_{127}^L / Y_{127}^H$ for $A \leq 130$ or $Y_{\mathcal{S}}^L / Y_{\mathcal{S}}^H = Y_{182}^L / Y_{182}^H$ for $A > 130$. The fraction of \mathcal{S} nuclei

contributed by H or L events to the corresponding solar r -process abundance are $F_r^H(\mathcal{S}) = 1/[1 + (Y_{\mathcal{S}}^L / Y_{\mathcal{S}}^H)(\Delta_H / \Delta_L)]$ or $F_r^L(\mathcal{S}) = 1 - F_r^H(\mathcal{S})$. From equation (1) the abundance of stable \mathcal{S} nuclei resulting from a single H or L event contaminating a standard mass of hydrogen in the ISM is $\log \epsilon_{\mathcal{H}}(\mathcal{S}) = \log \epsilon_{\odot, r}(\mathcal{S}) + \log F_r^H(\mathcal{S}) - \log(T_{\text{UP}} / \Delta_H)$ or $\log \epsilon_{\mathcal{L}}(\mathcal{S}) = \log \epsilon_{\odot, r}(\mathcal{S}) + \log F_r^L(\mathcal{S}) - \log(T_{\text{UP}} / \Delta_L)$. Here the spectroscopic notation $\log \epsilon(\mathcal{S}) \equiv \log(\mathcal{S}/\mathcal{H}) + 12$ is used (\mathcal{S}/\mathcal{H} being the number abundance ratio of \mathcal{S} to hydrogen). Thus, given ϑ , Δ_H , and Δ_L , there is a quantitative prediction for the abundances resulting from a single r -process event. For example, a single H event gives rise to $\log \epsilon_{\mathcal{H}}(\text{Eu}) \approx -3.0$ to -2.2 and $\log \epsilon_{\mathcal{H}}(\text{Ba}) \approx -2.1$ to -1.3 over a wide range of model parameters. The results from a mixture of multiple events can be calculated simply by adding the number of nuclei produced in each event and then converting it to the corresponding $\log \epsilon$ value for the mixture (see QW99).

3. THE IRON CONUNDRUM

Observational data (Gratton & Sneden 1994; McWilliam et al. 1995; McWilliam 1998; Sneden et al. 1996, 1998) on Ba/Eu, $\log \epsilon(\text{Eu})$, and [Fe/H] for low-metallicity stars are shown in Figure 1. As can be seen, there is a wide dispersion in $\log \epsilon(\text{Eu})$ at $-3.1 \lesssim [\text{Fe}/\text{H}] \lesssim -2.5$ while Ba/Eu is essentially constant. The r -process accounts for over 90% of the solar Eu inventory but only about 20% of the solar Ba inventory (Käppeler, Beer, & Wissak 1989; Arlandini et al. 1999). Consequently, the clustering of Ba/Eu around the solar r -process value exhibited in Figure 1 confirms the earlier proposal by Truran (1981) that heavy elements such as Ba in very metal-poor stars originated from the r -process. There are few Eu data at $-4 \lesssim [\text{Fe}/\text{H}] \lesssim -3$. However, sufficient Ba data at these metallicities (McWilliam et al. 1995; McWilliam 1998) are available and shown in Figure 2 (region A). Both Ba and Eu data show a wide dispersion at $-3.1 \lesssim [\text{Fe}/\text{H}] \lesssim -2.5$ (region B) and suggest that Fe and heavy r -nuclei are not coproduced by common supernovae (H events). The $\log \epsilon(\text{Ba})$ and $\log \epsilon(\text{Eu})$ values from a single H event in our model (QW99) are indicated by the zone marked “1 H” in the corresponding figure. We expect that increases of $\log \epsilon(\text{Ba})$ and $\log \epsilon(\text{Eu})$ above this zone are dominantly the results of adding more H events to the standard mixing mass of hydrogen. For example, if we take $\log \epsilon(\text{Eu}) \approx -2.5$ for HD 122563 ($[\text{Fe}/\text{H}] \approx -2.7$) as representative of a single H event, then the Eu abundance in CS 22892-052 ($[\text{Fe}/\text{H}] \approx -3.1$) would correspond to ~ 30 H events. As the Fe abundance in CS 22892-052 is smaller than that in HD 122563, it is evident that Fe cannot be significantly produced by H events. Thus the wide dispersion in Ba and Eu abundances at $[\text{Fe}/\text{H}] \sim -3$ poses a conundrum of Fe production in the early Galaxy and suggests that [Fe/H] is neither related to heavy r -element production nor a reliable chronometer (see QW99).

We find that the Fe conundrum can be resolved by postulating an initial or promptly-generated Fe inventory that existed before the occurrence of H and L events. By “initial” we mean very early stages during which an inventory of Fe was provided to the ISM from which regular stars later formed with no other temporal connection. Prompt Fe production is considered to be associated with

coevolution of all stars from an initial gas clot with no Fe. In both cases the mechanism for Fe production must have ceased at $[\text{Fe}/\text{H}] \sim -3$. Then non-Fe-producing H events and Fe-producing L events (see below) began to occur. The frequent occurrence of H events would result in a range of abundances for heavy *r*-elements such as Ba and Eu at $[\text{Fe}/\text{H}] \sim -3$ while the less frequent occurrence of L events would lead to increases in Fe abundance above $[\text{Fe}/\text{H}] \sim -3$. A correlation between $[\text{Fe}/\text{H}]$ and abundances of heavy *r*-elements would then be established when sufficient Fe was produced by L events to overwhelm the inventory produced by the initial/prompt Fe source which was not related to “typical” supernovae. The existence of some stars with $-4 \lesssim [\text{Fe}/\text{H}] \lesssim -3$ in region A of Figure 2 indicates that the initial/prompt Fe production had diverse yields and/or was sufficiently extended in time so that $[\text{Fe}/\text{H}] \sim -3$ represents the sum of a number of individual events. The Ba abundances in region A could be attributed to production by the initial/prompt Fe source which would be small compared with that by a single H event. However, these data could also be explained by a mixing scenario with no Ba production by the initial/prompt Fe source (see §4). The onset of the correlation between $[\text{Fe}/\text{H}]$ and abundances of heavy *r*-elements can be estimated as follows. By attributing $\sim 1/3$ of the solar Fe inventory (Timmes, Woosley, & Weaver 1995) to the Type II supernovae associated with L events, we expect a single L event to result in $\log \epsilon_L(\text{Fe}) \sim 5.0$ corresponding to $[\text{Fe}/\text{H}] \sim -2.5$ if we take $\Delta_L \sim 10^8$ yr (~ 100 L events are then responsible for the part of the solar Fe inventory contributed by Type II supernovae). Therefore, we expect that a correlation between $[\text{Fe}/\text{H}]$ and abundances of heavy *r*-elements would be established through addition of H and L events over a few 10^8 yr during which the ISM was sufficiently enriched by L events to $[\text{Fe}/\text{H}] \gtrsim -2.5$. Indeed, data in Figures 1 and 2 (region C) show that such a correlation exists at $[\text{Fe}/\text{H}] \gtrsim -2.5$.

4. DISCUSSION AND CONCLUSIONS

There is a basic issue of what plausible mechanism could account for the initial or promptly-generated Fe inventory. The prompt Fe production in a gas clot must have lasted for only a narrow time interval ($\ll \Delta_H \sim 10^7$ yr) and then was greatly diminished. A possible mechanism would involve Fe production by supermassive stars with no significant coproduction of heavy *r*-nuclei. Let us consider a pristine gas clot of mass M_0 from which two populations of stars could be made: supermassive stars with very short lifetimes ($\lesssim 10^6$ yr) and less massive stars with lifetimes longer than $\sim 10^6$ yr. So $M_F(t) + M_P(t) + M_g(t) = M_0$, where $M_F(t)$, $M_P(t)$, and $M_g(t)$ represent the masses stored in supermassive (“Fat”) stars, less massive (“Petite”) stars, and gas at time t . Taking the birth rates of both types of stars to be proportional to $M_g(t)$ and assuming that supermassive stars were born at about the same rate as they were destroyed, we have $\dot{M}_F(t) \approx K_F M_g(t) - M_F(t)/\bar{\tau}_F \approx 0$, where $\bar{\tau}_F$ is the average lifetime of supermassive stars, and $\dot{M}_P(t) = K_P M_g(t)$. Thus, $M_F(t) \approx K_F M_0 \bar{\tau}_F \exp(-K_P t)$ and $M_P(t) \approx M_0 [1 - \exp(-K_P t)]$. Therefore, if the birth rate for less massive stars was sufficiently high to deplete the gas over a few 10^6 yr, then the population of super-

massive stars would decline on the same timescale. This would provide some diversity in Fe abundances in stars formed at very early times but effectively truncate further addition of Fe from supermassive stars.

Stars with masses $11 \lesssim M/M_\odot \lesssim 40$ are considered to become supernovae. Their lifetimes range from 6×10^6 yr to 2×10^7 yr (see Fig. 1 of Timmes et al. 1995). Meynet et al. (1994) gave a lifetime $\approx 3 \times 10^6$ yr for a $120 M_\odot$ star. Therefore, prompt Fe production in our model must be associated with supermassive stars of at least a few $100 M_\odot$. These stars are assumed to produce no significant amount of heavy *r*-nuclei but sufficient Fe to give $[\text{Fe}/\text{H}] \sim -3$ over a few 10^6 yr. As speculated above, the termination of prompt Fe production was caused by rapid depletion of gas through storage in less massive stars over a few 10^6 yr. Thus the initial star formation rate in a pristine gas clot of mass $\sim 10^6 M_\odot$ is required to be $\sim 1 M_\odot \text{ yr}^{-1}$. When extrapolated to the whole Galaxy, this corresponds to an initial rate $\sim 10^5 M_\odot \text{ yr}^{-1}$, much higher than the average value of $\sim 10 M_\odot \text{ yr}^{-1}$ over Galactic history. On a longer timescale, stars with $11 \lesssim M/M_\odot \lesssim 40$ became supernovae and began to enrich the ISM. These supernovae are of two types: high frequency H events and low frequency L events. Within a standard mass of hydrogen, H and L events occur on timescales $\sim 10^7$ yr and $\sim 10^8$ yr, respectively. The H events produce heavy *r*-elements but no Fe and this resulted in a wide range of abundances for heavy *r*-elements (e.g., Ba and Eu) at $[\text{Fe}/\text{H}] \sim -3$. A correlation between $[\text{Fe}/\text{H}]$ and abundances of heavy *r*-elements was established later through addition of H and L events over a few 10^8 yr when Fe production by L events overwhelmed the prompt Fe inventory. The observed onset of this correlation at $[\text{Fe}/\text{H}] \sim -2.5$ is consistent with the expected Fe yield of L events. The L events also produce light *r*-elements such as Ag. Production of these elements by the hypothesized prompt Fe source is unknown. It was argued that the first stars of H-He composition would be very massive (e.g., Truran & Cameron 1971). These stars would provide elements heavier than He to the ISM (e.g., Ezer & Cameron 1971). How much Fe would be produced by these stars and how this Fe would be mixed with the ISM require more investigation.

It is likely that supermassive stars would blow up their parent gas clots, thus preventing further star formation. In this case they would provide Fe to the general ISM. We speculate that once $[\text{Fe}/\text{H}] \sim -3$ was reached, supermassive stars could no longer be produced and less massive stars would form instead. In this scenario an initial Fe inventory could be provided without requiring a high star formation rate in the gas clots before the H and L events occurred. We note that the cut-off at $[\text{Fe}/\text{H}] \sim -3$ may correspond to a condition when sufficient amount of elements heavier than He was provided by supermassive stars to permit adequate cooling of aggregating matter for less massive ($\lesssim 40 M_\odot$) stars to form. A supermassive star of a few $100 M_\odot$ must produce a few M_\odot of Fe in order to give $[\text{Fe}/\text{H}] \sim -3$ to a clot of $\sim 10^6 M_\odot$.

Region A of Figure 2 deserves special attention. We are faced with Ba abundances below the production by a single H event at $-4 \lesssim [\text{Fe}/\text{H}] \lesssim -3$. These Ba abundances could be attributed to minor heavy *r*-element production by supermassive stars. However, supernova explo-

sions could drive gas outflows from a clot. The enriched gas could then mix with the pristine gas in other clots. In this way Ba abundances below the production of a single H event for $[\text{Fe}/\text{H}] < -3$ could be obtained. For example, the abundances in the star at the left corner of region A could be explained by a mixture of gas outflow after an H event with the gas in a pristine clot (mixing ratio $\sim 1:10$). We have avoided the complexities of mixing and exchange in our previous discussion based on a standard mixing mass. Subsequent models must address these issues.

The chronometric interpretation of $[\text{Fe}/\text{H}]$ is complex. Condensation of matter to form stars during the early evolution of the Galaxy is expected to have been greatly extended in space and time ($\sim 10^8$ – 10^9 yr). This means that clots of baryonic matter formed within the Galaxy at widely disparate times. The model proposed here only requires the following sequence of events to occur within a clot: an initial Fe inventory from or prompt Fe enrichment by supermassive stars, enhancement in heavy *r*-elements by H events, and enrichment in Fe and light *r*-elements by L events. So long as different clots of baryonic matter within the Galaxy underwent the same evolution, this sequence of events can be established independent of which

stars observed today represent the same initial clot. However, this same sequence of events might have started at widely different times within different clots. In this sense, until chemical enrichment became essentially uniform on the Galactic scale, stellar abundances at low metallicities would only reflect relative time in the above sequence. Finally, if galaxies formed $\sim 10^9$ yr after the Big Bang, the epoch of supermassive star formation discussed here would correspond to a redshift of at least $z \sim 4$ [for which the age of the universe is $\sim 10^{10}(1+z)^{-3/2} \sim 10^9$ yr]. This epoch is earlier than the one probed by recent abundance observations at “high” redshifts ($z \sim 3$, Pettini et al. 1997).

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FIG. 1.— Data (stars: Gratton & Sneden 1994; squares: McWilliam et al. 1995; McWilliam 1998; triangles: Sneden et al. 1996; 1998) on $[\text{Ba/Eu}]_r \equiv \log(\text{Ba/Eu}) - \log(\text{Ba/Eu})_{\odot,r}$ and $\log \epsilon(\text{Eu})$ versus $[\text{Fe/H}]$ for low-metallicity stars. The Ba/Eu ratio is near the solar r -process value over the range of $[\text{Fe/H}]$ shown. But there is a wide dispersion in $\log \epsilon(\text{Eu})$ at $-3.1 \lesssim [\text{Fe/H}] \lesssim -2.5$. This dispersion disappears for $[\text{Fe/H}] \gtrsim -2.5$.

FIG. 2.— Data (symbols as in Fig. 1) on $\log \epsilon(\text{Ba})$ versus $[\text{Fe/H}]$ for low-metallicity stars. The range of $[\text{Fe/H}]$ extends about one dex below that for the existing data on Eu. There is a wide dispersion in $\log \epsilon(\text{Ba})$ at $-3.1 \lesssim [\text{Fe/H}] \lesssim -2.5$. Three regions of abundance evolution are schematically shown: production by the initial/prompt Fe source (A), addition of high frequency non-Fe-producing H events (B), and mixture of H and low frequency Fe-producing L events (C).



